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Short Communication

Effects of Soil Compaction and Tillage Practices on Carbon Dioxide Efflux in Northeast China: Evidence from an Incubation Study

Xuewen Chen[1]*, Jingmin Yang[2], Aizhen Liang[1], Xiaoping Zhang[1]

[1]Key Laboratory of Mollisols Agroecology, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun, 130102, China
[2]College of Resource and Environment, Jilin Agricultural University, Changchun, 130118, China

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Abstract

Limited information is available for how soil compaction affects carbon dioxide (CO_2) efflux under different tillage systems. To improve understanding of the effects of compaction and tillage on soil CO_2 efflux, an incubation study consisting of no tillage (NT), moldboard plow (MP), and ridge tillage (RT) was conducted to explore the relationships between CO_2 efflux and bulk density, as well as pore size distribution under different levels of bulk densities, and the thresholds of bulk density and the volume of pore size above which CO_2 efflux were affected in northeast China. Results showed that there was a significantly negative correlation (r = -0.990, $p<0.05$; r = -0.986, $p<0.05$; and r = -0.992, $p<0.01$, respectively, for NT, MP, and RT) between CO_2 efflux and bulk density, whereas the correlation was significantly positive (r ranges from 0.75 to 0.85, $p<0.05$ for each tillage practice under bulk densities of 1.0-1.6 g/cm^3) for the volume of small macropores (30-100 μm). The critical value of bulk density for impeding CO_2 efflux was more produced in 1.6 g/cm^3 and the volume of small macropores affected CO_2 efflux variation greatly. Ridge tillage is a better tillage practice for impeding soil CO_2 efflux than no tillage, as evidenced by the lesser volume of small macropores.

Keywords: soil compaction, soil CO_2 efflux, soil bulk density, small macropores, ridge tillage

Introduction

Soil carbon dioxide (CO_2) efflux is one of the most important components of the ecosystem carbon (C) budget, so even a small change in soil respiration will impact global C dynamics [1]. Many previous studies have focused on the effects of soil temperature, moisture content, aeration, and diffusivity on CO_2 efflux [2]; however, much less is known about how soil compaction affects CO_2 efflux. Soil compaction increases bulk density, decreases porosity, and restricts fluid and gas transport processes, thereby affecting CO_2 efflux [3]. Although some field studies have evaluated the effects of soil compaction on CO_2 efflux [4-5], most of these studies are restricted to the analysis of a qualitative relationship between soil bulk density or total porosity and CO_2 efflux. The critical value of soil bulk density and the volume of which pore size affects CO_2 efflux changes remain unexplored. De Neve and Hofman [6] proposed a threshold value

*e-mail: chenxuewen@iga.ac.cn

of 1.6 g/cm^3 for bulk density, above which C mineralization rate was strongly depressed in an incubation experiment, but it is not yet clear whether or not 1.6 g/cm^3 is a suitable critical value. There is still only limited information for soil pore size distribution. Knowledge about the changes in soil pore size distribution may provide additional insight on the C decomposition processes and why C may accumulate in different pore classes [7]. Hence, there is a desire to analyze the different compactness (bulk density) together with pore size distribution effects in order to more accurately understand the effect of compaction on CO_2 efflux.

Measuring soil CO_2 efflux is crucial for accurately evaluating the effect of soil management practices on global C cycling [8]. As a key element in conservation agriculture, conservation tillage was shown to have lower soil CO_2 efflux than conventional tillage in some studies, but it also may lead to excessive soil compaction [9]. Tillage-induced changes in compaction affect the ability of soil to fulfil essential soil functions in relation to soil respiration [4]. However, the effect of soil compaction caused by tillage practices on CO_2 efflux is as yet largely unknown. Thus, research is needed to analyze the effects of soil compaction and tillage practices on CO_2 efflux. To our knowledge, ridge tillage (RT) is not as common as moldboard plow (MP) and no tillage (NT), and little effort has been expended on the influence of RT on soil CO_2 efflux. More data in the comparison of soil CO_2 efflux under NT, MP, and RT are required for the adoption of conservation tillage practices. The objectives of this study were to determine the relationships between CO_2 efflux and bulk density, as well as pore size distribution under different levels of soil bulk densities, and then identify the thresholds of bulk density and the pore size volume above which CO_2 efflux were affected under NT, MP, and RT in northeast China.

Material and Methods

Experimental Site and Treatments

The study area was initiated in 2001 at the Experimental Station (44°12′N, 125°33′E, 205 m a.s.l.) of the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, in Dehui County, Jilin Province, China. The type of soil in the current study was a clay loam soil (Typic Hapludoll) and some of its selected physical and chemical properties were presented in Table 1 [10]. Soil pH in the 0-20 cm layer was approximately 6.5, classified as neutral or slightly acidic. The climate was a semi-humid temperate continental monsoon. The mean annual temperature is 4.4ºC, and the mean annual precipitation over the past 30 years is 520 mm. More than 70% of the annual precipitation occurred in June, July, and August. Before the establishment of the current tillage experiment, the land had been used to grow monoculture maize under conventional management for more than 10 years.

The tillage treatments, consisting of NT, MP, and RT, were arranged in a randomized complete block design with four replicates. The tillage treatment was applied to the main plots, which were 10.4 m x 20 m; each main plot was split lengthwise into two 5.2 m x 20 m sub-plots. Different crop rotations were applied at the sub-plot level: corn-soybean (C-S) with both crops present each year under NT, MP, and RT; and continuous corn (C-C) under NT and MP. Tillage treatments employed in the experiment were used in this study, including the C-S under NT, MP, and RT. NT had no soil disturbance except for planting using a KINZE-3000 NT planter (Kinze Manufacturing Inc., Williamsburg, USA). MP included one fall MB plowing (approximately 20 cm in depth) after harvest, one spring disking (7.5 to 10 cm in depth), ridge-building before planting, and the crop under MP had two tillage practices after planting. RT included ridge-building in June, corn root chopping in fall (approximately 1/3 row width), and no other soil disturbance after harvest and permanent ridge planting in the next year, and the crop was cultivated three times after planting. Because a planter was used for seeding in this study, so it was not necessary to prepare the seed bed beforehand.

Different fertilizer doses were used for different crops. For corn, 100 kg N/ha, 45.5 kg P/ha, and 78 kg K/ha were applied each year as starter fertilizer, with an additional 50 kg N/ha applied as top dressing at the sixth-leaf stage (V6). For soybean, all fertilizers were applied as starter fertilizer, including 40 kg N/ha, 60 kg P/ha, and 80 kg K/ha. Since the main objective of the present study was to determine the effects of soil compaction and tillage on CO_2 efflux, different fertilizer doses' effects on soil CO_2 efflux were not considered.

Soil Sampling and Analysis

In spring 2014, before the maize planting, soil samples were collected down to a depth of 10 cm from each NT,

Table 1. Selected physical and chemical properties of the studied soil [10].

Depth (cm)	pH	Clay (%) (<2 μm)	Silt (%) (2-20 μm)	Sand (%) (20-200 μm)	Bulk density (g/cm^3)	Soil organic carbon (g/kg)	Total soil nitrogen (g/kg)
0-5	6.48	36.03	24.00	39.97	1.24	16.48	1.42
5-10	6.45	35.83	23.78	40.39	1.38	16.29	1.39
10-20	6.51	35.68	24.35	39.98	1.36	16.08	1.37
20-30	7.03	36.56	25.00	38.72	1.38	14.22	1.16

MP, and RT plot, and air-dried. After manually removing visibly identifiable crop residues, soil was ground to pass through a 0.25 mm sieve. Then three replicates of 500 g dry soil for each treatment were packed into 10 cm diameter × 10 cm poly vinyl chloride (PVC) tubes. Since the optimal soil bulk density range for field-crop production and the range where root elongation become severely restricted was 1.0-1.6 g/cm^3 [11] in northeast China (especially Jilin Province), the treated soil was uniaxially compacted to four levels of dry bulk density (1.0, 1.2, 1.4, and 1.6 g/cm^3) using a compaction cylinder with a diameter equal to the inner diameter of the PVC tube and hydraulic press. Because the base area of the PVC tube and weight of soil column were constant value, the desired different bulk density soils were obtained by adjusting different vertical pressure applied at the top of the PVC tube until the desired height of the soil column was achieved. The tops and bottoms of PVC tubes were covered with gas-permeable parafilm and perforated at the top. The total weight of each PVC tube was recorded. These samples were incubated in a MEMMERT HPP750 Constant Climate Chamber (Memmert Inc., Schwabach, Germany). The incubation temperature was 25ºC. Moisture content was monitored regularly by weighing the tubes and kept constant throughout the incubation by adding distilled water as required.

Soil CO_2 efflux was measured at 1, 2, 4, 6, 10, 14, 18, 26, 34, and 42 days after the start of the incubation with an LI-COR 820 gas analyzer (Li-Cor Biosciences Inc., Lincoln, USA). The principle and procedure of measurement were as follows: an enclosed dynamic system was built with PVC tube and LI-COR 820 gas analyzer; soil CO_2 concentration in the enclosed dynamic system was real time dynamic monitored by a LI-COR 820 gas analyzer in 120 seconds, linear regression was made with soil CO_2 concentration and measuring time, and then the rate of change of soil CO_2 concentration (a) in the enclosed dynamic system was calculated. Soil CO_2 efflux was determined by the following equation:

$$F = (a \times V) / (Vm \times m) \quad (1)$$

...where F is soil CO_2 efflux (mol·(g·s)$^{-1}$), a is the rate of change of soil CO_2 concentration (ppm·(s)$^{-1}$, ppm represents part per million (and it is a dimensionless quantity), V is the volume of enclosed dynamic system (L), Vm is molar volume of soil CO_2 (L·(mol)$^{-1}$), and m is the weight of incubated material (g). A detailed diagrammatic sketch of the enclosed dynamic system for soil CO_2 efflux measuring was provided in Fig. 1.

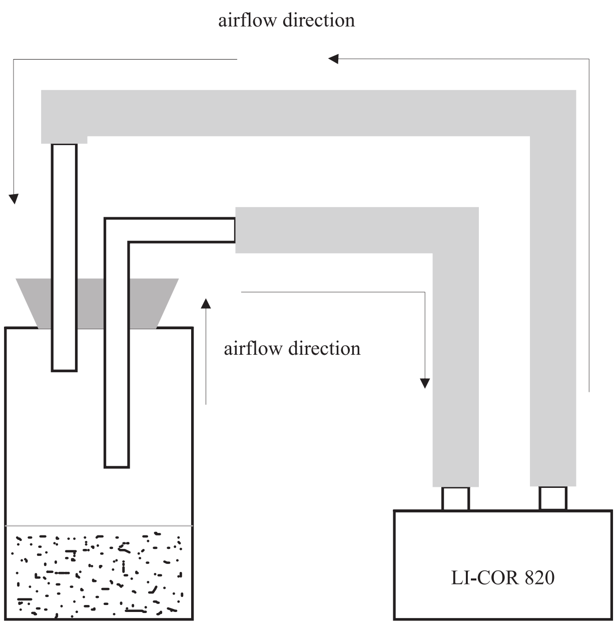

Fig. 1. Diagrammatic sketch of the enclosed dynamic system for soil carbon dioxide (CO_2) efflux measuring.

Another three replicates of packed soil cores for each tillage and bulk density treatment were prepared as above for determining the pore size distribution before incubation. Soil water retention curves were collected using a 1500 Pressure Plate (0-1500 kPa pressure potential range; Soil Moisture Equipment Inc., Santa Barbara, USA). Soil pore size distribution was computed from the soil water retention data using the relationship between distribution of pore size and capillary water retention [12]. Equivalent pore diameter (EPD) of a given matric pressure was estimated according to the following equation:

$$EPD = 300/h \quad (2)$$

...where EPD was the diameter of the smaller pores drained (μm) and h was the soil water pressure potential (kPa) [12]. Soil pore size distribution after incubation were also determined by the same method above. After determining soil pore size distribution, the above undisturbed soil samples were finally oven dried at 105ºC for 24 h to obtain bulk density after incubation.

Statistical Analysis

SPSS 13.0 (SPSS Inc., Chicago, USA) software was used for all of the statistical analyses. Treatment main effects on soil CO_2 efflux, bulk density, and pore size distribution before and after incubation were tested using one-way analysis of variance. Treatment means were compared using the least significant difference at $p<0.05$. Relationships between soil CO_2 efflux and bulk density, and pore size distribution were determined using Pearson linear correlation analysis.

Results and Discussion

Relationship between Soil CO_2 Efflux and Lulk Density

Soil CO_2 efflux significantly decreased ($p<0.05$) with increasing bulk density in each tillage system during the incubation period (Figs 2-3). Similar results reported by Mordhorst et al. [4] indicated that soil compaction directly

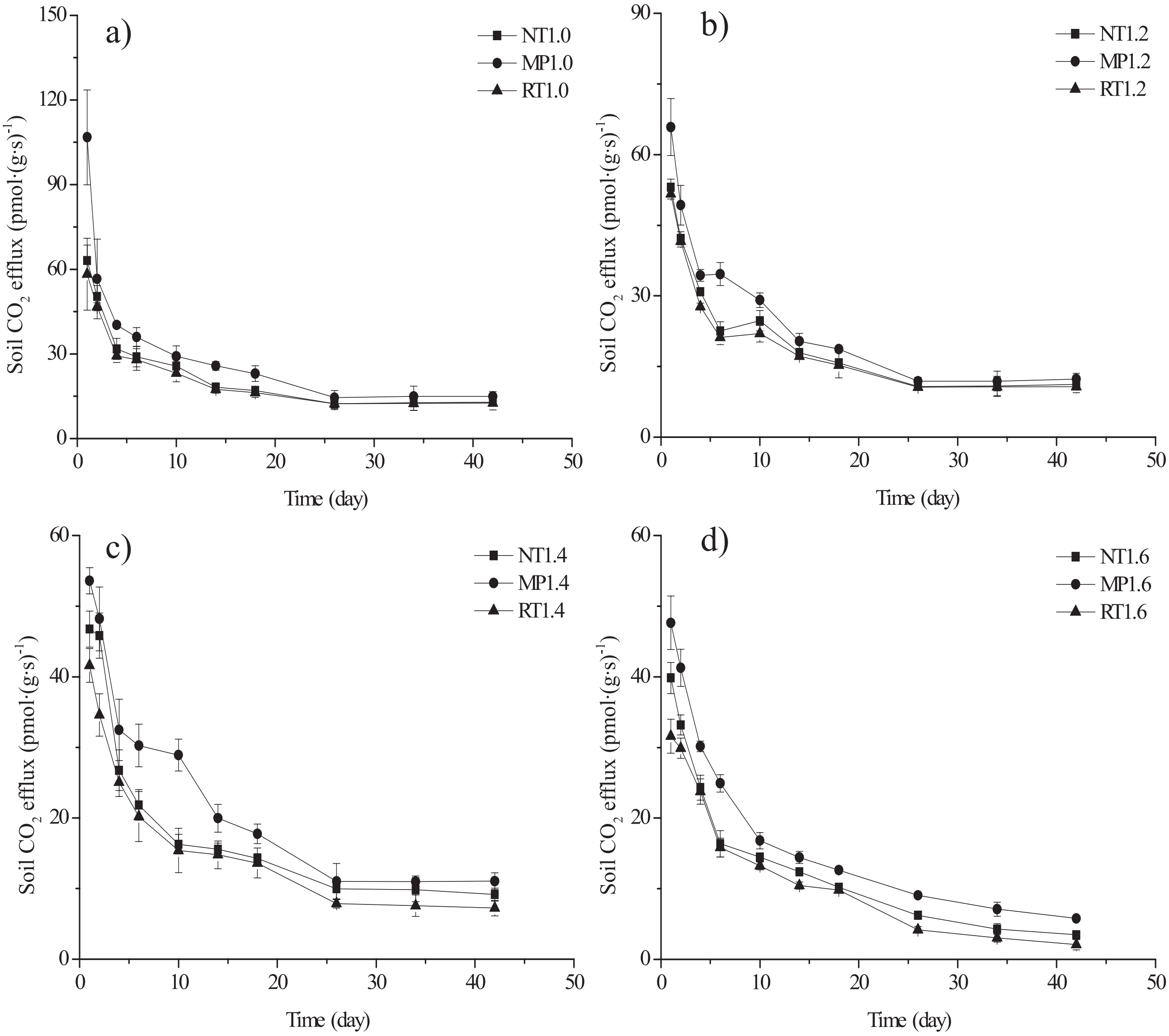

Fig. 2. Average soil carbon dioxide (CO_2) efflux at different levels of soil bulk densities under no tillage (NT), moldboard plow (MP), and ridge tillage (RT) systems for a 42-day incubation period; a), b), c), and d) represent soil bulk densities of 1.0, 1.2, 1.4, and 1.6 g/cm^3, respectively; pmol·(g·s)$^{-1}$ represents pico mol·(g·s)$^{-1}$.

resulted in the lower CO_2 efflux from compacted soils. In terms of tillage practices, NT and RT led to significant soil CO_2 efflux decrement before 26 days (p<0.05); however, MP did not show the obvious variation trend (Figs 2-3). This could be attributed to the difference in soil aeration that was induced by tillage intensity between conservation and conventional tillage systems. Though NT resulted in similar soil CO_2 efflux with RT, the latter was on average 4.12% lower than the former before 26 days (Fig. 2). Soil CO_2 efflux values after 26 days of incubation became stable under each level of bulk density (except 1.6 g/cm^3) (Figs 2-3).

Soil CO_2 efflux had significant negative relationships with bulk density under each tillage practice (Fig. 4). Similar observations were also reported by Setia et al. [13] and Nawaz et al. [3], who found a significant negative correlation of soil bulk density with CO_2 efflux. This occurs as increases in soil bulk density reduce gas diffusivity, which is linked with oxidation rate, and consequently rates of soil respiration and CO_2 emission [14]. Sleutel et al. [15] also attributed reduced CO_2 efflux in compacted soil to reduced gas diffusivity rather than to any direct influence on the function of the soil microbial community. Pearson correlation coefficients between soil CO_2 efflux and bulk density were greater under RT than NT, and for the RT plot achieved a markedly significant correlation (p<0.01) (Fig. 4). This indicated that CO_2 efflux in RT was more depressed with higher soil bulk density compared to the NT soil.

As seen from Figs 2 and 3, CO_2 efflux decreased in the whole incubation at soil bulk density of 1.6 g/cm^3. This result indicated that 1.6 g/cm^3 was the suitable critical value of bulk density for relatively unimpeded soil CO_2 efflux under different tillage treatments of the current study. It was also in accordance with the maximum value where root elongation became severely restricted [16].

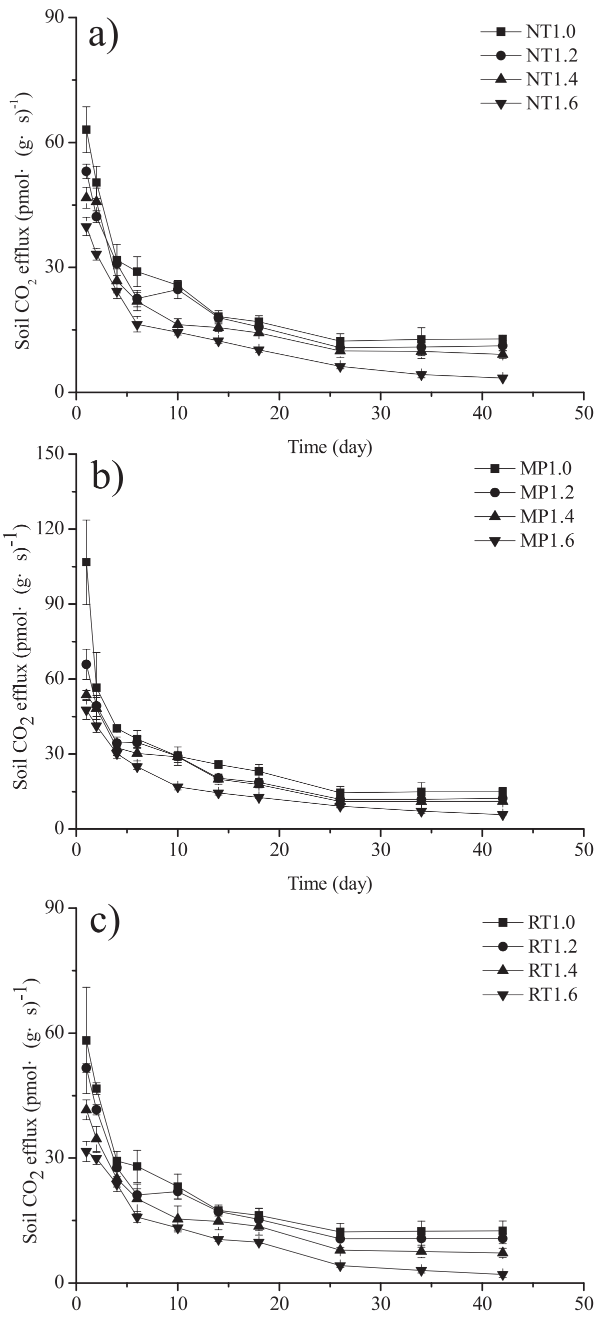

Fig. 3. Average soil carbon dioxide (CO_2) efflux for one tillage practice (no tillage (NT), moldboard plow (MP) and ridge tillage (RT)) under different bulk density values (1.0, 1.2, 1.4, and 1.6 g/cm^3) for a 42-day incubation period; a), b), and c) represent NT, MP, and RT, respectively; pmol·(g·s)$^{-1}$ represents pico mol·*(g·s)*$^{-1}$.

Relationship between Soil CO_2 Efflux and Pore Size Distribution

Soil pore size distribution was presented as pore volume occurring within a given size interval per unit soil (total) volume [17]. Although numerous criteria had been used to define pore size classes, pores > 100 µm are often classified as large macropores, and 30 µm is often

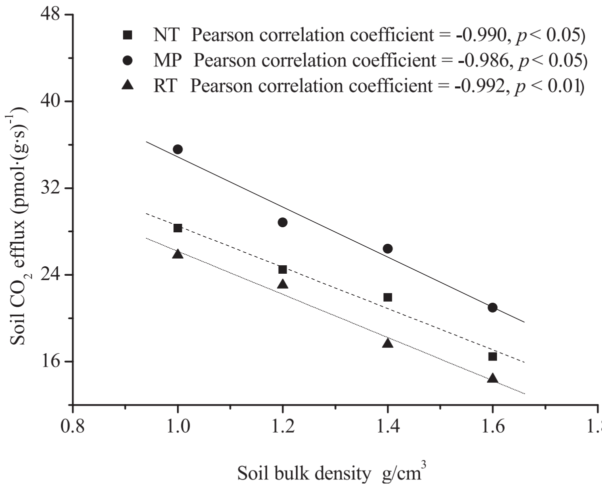

Fig. 4. The relationship between soil carbon dioxide (CO_2) efflux and bulk densities under no tillage (NT), moldboard plow (MP), and ridge tillage (RT) systems.

taken as the boundary between small macropores and mesopores, and pores of <0.2 µm are generally referred to as micropores [18]. Hence, pore size distribution in the current study was categorized into four classes: large and small macropores (>100 µm and 30-100 µm, respectively), and meso- (0.2-30 µm) and micropores (<0.2 µm).

The volume of small macropores was significantly ($p<0.05$) less in NT and RT than MP under each soil bulk density before incubation (Table 2). This could be due to the partial destruction of large macropores by soil disturbance, resulting in the formation of a greater volume of small macropores under MP. Kay and VandenBygaart [19] reported in their review that converting from conventional to conservation tillage generally resulted in a decreased volume fraction of pores 30-100 µm. Though NT and RT systems gave a similar volume of small macropores, the latter was on average 5.89% lower than the former (Table 2). This was due to the different soil disturbances in the NT and RT plots. Ridge tillage refers to management practices with reduced penetration depth and without topsoil inversion, leading to a decrement in small macropores [20]. No significant differences in the volume of large macro-, meso-, and micropores were observed among NT, MP, and RT before incubation (Table 2). Feiza et al. [7] also reported that no significant difference in large macro-, meso-, and micropore categories under conventional and conservation tillage systems. A similar trend was also found for the soil pore size distribution after incubation (Table 2). Soil bulk densities, and large macro-, meso-, and micropores under each tillage system did not change before and after incubation, but a significant decrease was found in small macropores after rather than before incubation (Table 2) ($p<0.05$). Therefore, the differences in pore size distribution before and after incubation were more pronounced in small macropores and tillage had a profound impact on small macropores.

In the correlation analysis of soil CO_2 efflux to small macropores under different tillage treatments and bulk

Table 2. Soil bulk density and pore size distribution under no tillage (NT), moldboard plow (MP), and ridge tillage (RT) systems before and after incubation.

Incubation	Bulk density (g/cm^3)	Tillage	Soil pore size distribution			
			Large macropores (%)	Small macropores (%)	Mesopores (%)	Micropores (%)
Before	1.0a	NT	12.06a	0.52c	34.16a	15.52a
	1.0a	MP	11.88a	0.92a	34.13a	15.33a
	1.0a	RT	11.95a	0.49c	34.35a	15.47a
After	1.0a	NT	12.02a	0.44d	34.31a	15.49a
	1.0a	MP	11.87a	0.82b	34.26a	15.31a
	1.0a	RT	12.02a	0.41d	34.42a	15.41a
Before	1.2a	NT	10.02a	0.45c	30.76a	13.49a
	1.2a	MP	9.87a	0.86a	30.58a	13.41a
	1.2a	RT	9.98a	0.43c	30.72a	13.59a
After	1.2a	NT	9.99a	0.39d	30.53a	13.81a
	1.2a	MP	9.75a	0.78b	30.67a	13.52a
	1.2a	RT	9.89a	0.36d	30.78a	13.69a
Before	1.4a	NT	8.01a	0.34c	26.95a	11.87a
	1.4a	MP	7.85a	0.75a	26.84a	11.73a
	1.4a	RT	7.96a	0.32c	26.91a	11.98a
After	1.4a	NT	7.95a	0.29d	26.97a	11.96a
	1.4a	MP	7.82a	0.68b	26.84a	11.83a
	1.4a	RT	7.93a	0.27d	26.98a	11.99a
Before	1.6a	NT	6.89a	0.23c	22.64a	9.86a
	1.6a	MP	6.73a	0.66a	22.51a	9.72a
	1.6a	RT	6.58a	0.22c	22.86a	9.96a
After	1.6a	NT	6.71a	0.19d	22.85a	9.87a
	1.6a	MP	6.66a	0.59b	22.66a	9.71a
	1.6a	RT	6.62a	0.18d	22.95a	9.87a

Values followed by the same letter within a column at the same level of bulk density before and after incubation indicate no significant difference at the 0.05 level.

densities, the data showed a significant ($p<0.05$) positive correlation between soil CO_2 efflux and the volume of small macropores at NT, MP, and RT plots (Table 3). This result means that although small macropores represent a small portion of soil total porosity, they explain most CO_2 efflux variation. This also implied that even with a slight change in the volume of small macropores (30-100 μm), soil CO_2 efflux will also be affected. The results from the present study confirmed the finding by Sleutel et al. [15] that soil pore size distribution could play an important regulatory role in C decomposition processes and C may accumulate in different pore classes. With regard to different soil pores, only small macropores affected CO_2 efflux significantly. This could be owing to the different soil functions in different soil pores. Small macropores are responsible for optimizing both gas and water fluxes simultaneously in soil [18]. However, large macropores constitute free spaces where plant roots can grow or earthworm activity prevails [19]. Mesopores are particularly important for the storage of water for plant growth [7]. In addition, micropores retain water generally not available to plants and their small diameter restricts microbiological activity [12]. Hence, no significant effects on soil CO_2 efflux were observed for large macro-, meso-, and micropores. On the other hand, tillage practices through differences in mechanical disturbances altered physical changes in pore systems, which controled CO_2 efflux by changes in gas transport properties [4]. In other

Table 3. Pearson correlation coefficients (r) between soil carbon dioxide (CO_2) efflux and the volume of small macropores (30-100 μm) under different bulk densities and no tillage (NT), moldboard plow (MP), and ridge tillage (RT) systems.

Bulk density (g/cm^3)	Tillage	*r*	*P* > *F*
1.0	NT	0.78	0.015
	MP	0.75	0.022
	RT	0.81	0.014
1.2	NT	0.79	0.015
	MP	0.76	0.021
	RT	0.82	0.014
1.4	NT	0.81	0.014
	MP	0.77	0.018
	RT	0.84	0.013
1.6	NT	0.83	0.013
	MP	0.78	0.015
	RT	0.85	0.012

F is the statistics of F-test

words, RT had a smaller volume of small macropores, which led to a decrement in soil CO_2 efflux compared to NT in this study. In addition, the RT system has been proposed as a compromise between MP and NT [16]. Therefore, it is better to use RT as as a tillage system option for impeding soil CO_2 efflux. From the above analysis, we obtained the relationships between CO_2 efflux and bulk density as well as pore size distribution under different levels of soil bulk densities, and the thresholds of bulk density and the volume of which pore size above which CO_2 efflux were affected under NT, MP, and RT. The reasons why this study was focused on the laboratory experiment are as follows: firstly, field research cannot simulate and investigate the different compactness (bulk density) effect. Secondly, though the incubation experiment cannot be considered real, evidence from an incubation study may be useful for providing a valuable basis to choose appropriate soil management practices for C sequestration in northeast China.

Conclusions

Based on the incubation experiment, soil CO_2 efflux was significantly negatively related with bulk density and positively related with the volume of small macropores (30-100 μm). 1.6 g/cm^3 was the suitable critical value of bulk density for impeding soil CO_2 efflux and the volume of small macropores (30-100 μm) accounted for most soil CO_2 efflux changes under each tillage practice. Compared with NT, RT performed as a better tillage practice for impeding soil CO_2 efflux due to the decreased volume of small macropores (30-100 μm) in northeast China.

Acknowledgements

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